Epitaxial Growth of Tensile Strained GeSnC

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Background

Ge has a nearly direct bandgap: the energy difference between the direct bandgap and the indirect bandgap is very small (~140 meV). Tensile strain and alloying are the two most common approaches to make Ge-based direct bandgap materials.

Although $Ge_{1-x}Sn_x$ becomes a direct bandgap material with x>8%, strained growth on Ge or GaAs adds undesirable compressive strain.[1,2] Worse, the very small electron effective mass ($m_e^* \approx 0.02m_0$) loses the direct bandgap when confined in a quantum well or dot.[3]

Our group has previously demonstrated that $Ge_{1-y}C_y$ with y ≈ 1% has a direct bandgap, and we previously grew GeC using a special precursor (4GeMe) as a C source with no defects detectable in TEM[4,5].

In this work, we instead grew $Ge_{1-x-y}Sn_xC_y$ using commercially available carbon tetrabromide (CBr_4). GeSnC adds additional control in epitaxial growth: Sn and C partially compensate local strain and distortion of the host Ge bonds. This is likely to increase both C and Sn substitutional incorporation and provides a more stable material.

We believe C-C pairs are likely defects in the carbon containing alloys, so we also used atomic hydrogen to help reduce those defects.

These results suggest two routes to direct bandgap Group IV materials for active silicon photonics such as lasers and amplifiers.

Research Problem

Group III-V semiconductors provide superior optoelectronic properties owing to their direct bandgap and this enables their versatile uses in photonic devices such as laser, amplifiers etc. However, they have a different crystal structure from Si which introduces significant challenges in integration of those devices on Si. Unlike group III-V materials, all group IV semiconductors are indirect bandgap and that's why they are poor light emitters. Therefore, the motivation of this project is to develop a direct bandgap group IV material which can be later used in Si photonics as a laser source.

Growth Method

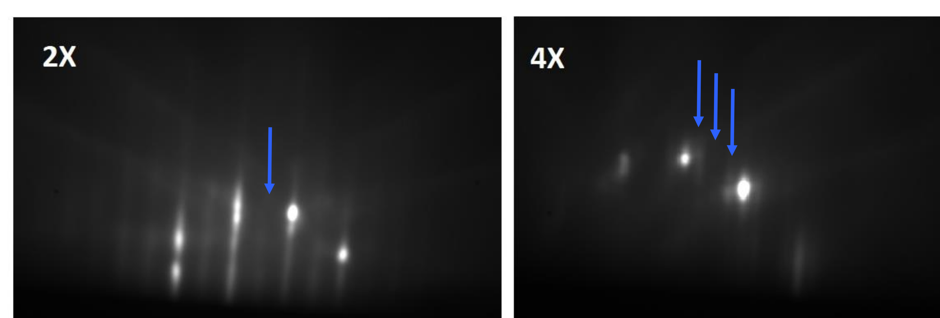
Growth method: Molecular Beam Epitaxy
Solid source: Ge, Sn
Gas source: CBr_4, Atomic hydrogen source
Base pressure: 1×10^{-9} Torr
Growth temperature: 215 ℃

Beam flux and shutter were used for composition and thickness control

Atomic hydrogen was used for oxide desorption

Ge Cap (10 nm)
GeSnC (200 nm)
Ge Buffer (150 nm)
GaAs (sub)

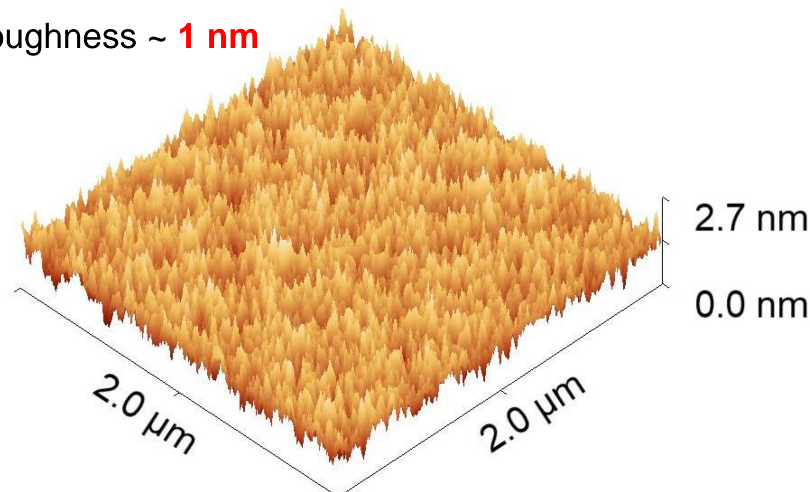
In-situ RHEED demonstrated flat oxide free surface reconstruction (2 × 4)



Native oxide desorption from GaAs substrate

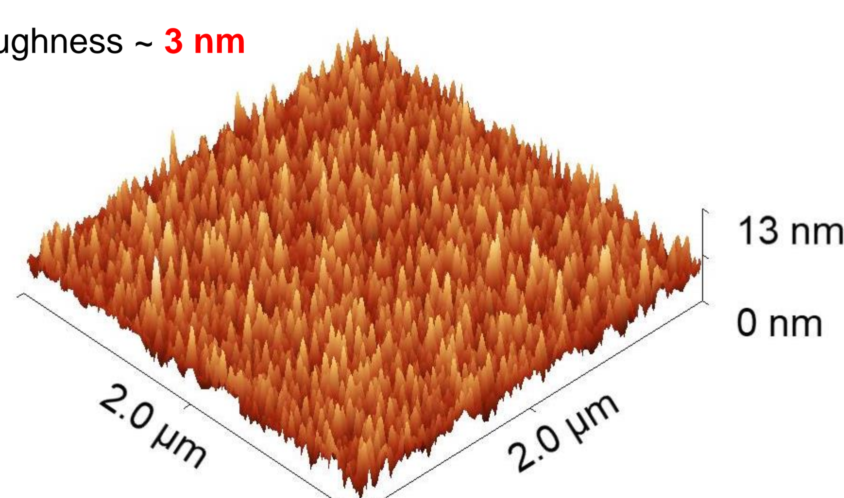
Surface Morphology: Atomic Force Microscopy

RMS Roughness ~ 1 nm



AFM image of GeSnC surface without atomic H

RMS Roughness ~ 3 nm

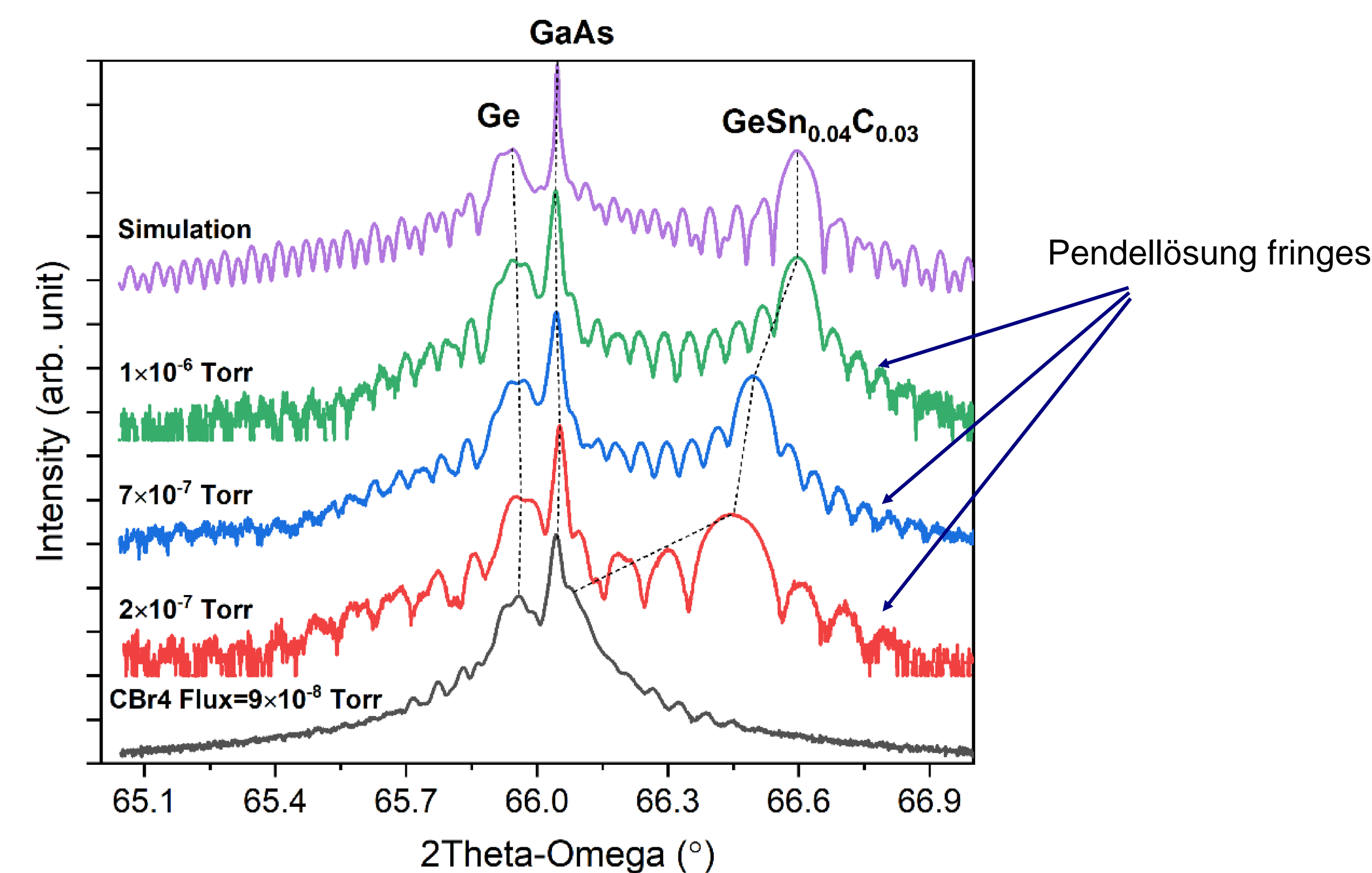


AFM image of GeSnC surface with atomic H

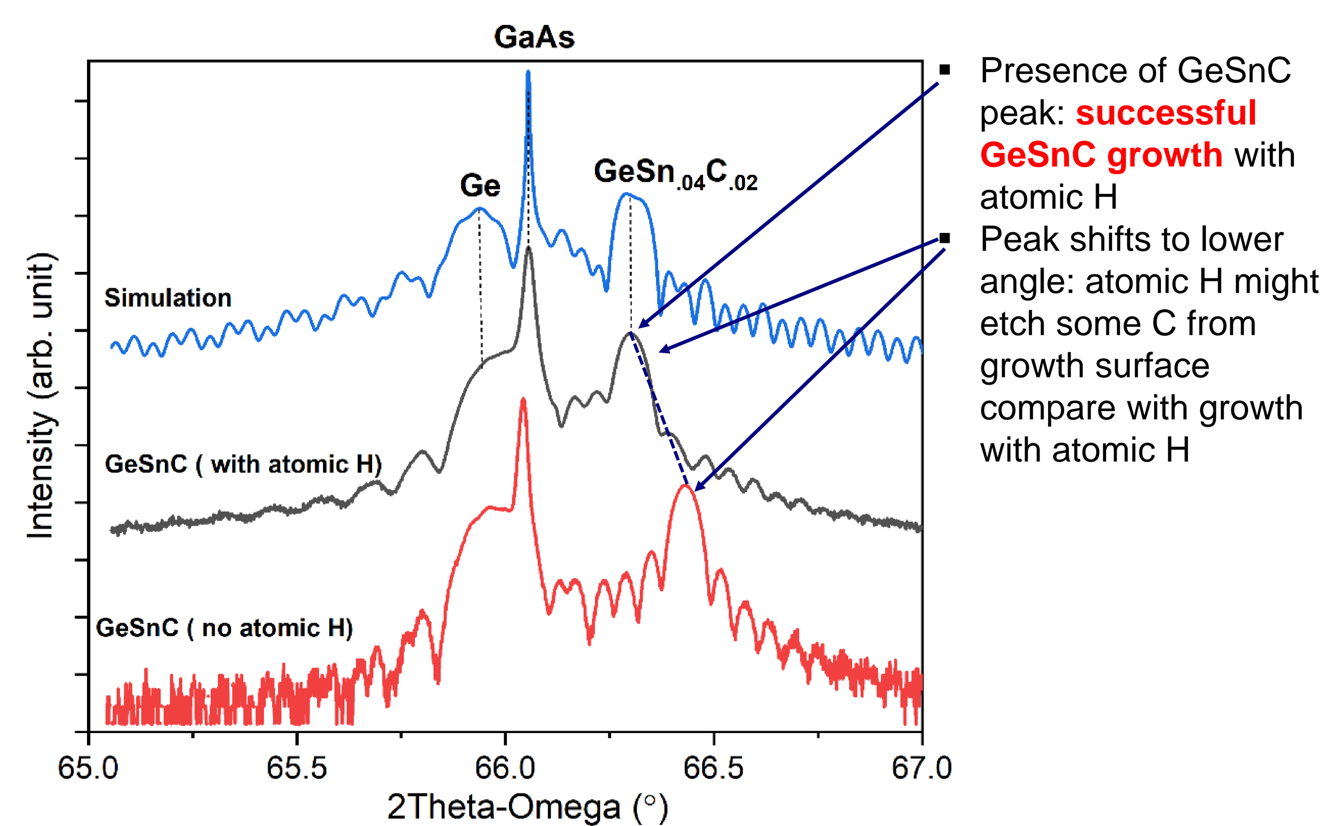
✓ Atomically flat surface in both approaches (with or without atomic H)

Crystal Quality: XRAY Diffraction (XRD)

- At low CBr_4 flux the carbon incorporation is lower
- At high CBr_4 flux, GeSnC peak shifts to higher angle indicating higher substitutional carbon incorporation
- Substitutional incorporation (simulated): Sn= 4% and C=3%
- Pendellösung fringes are present in all sample indicating flat and coherent interface
- Line width (FWHM) GeSnC is small (~42 arc-sec) indicating good crystal quality



XRD ω-2θ scans about GaAs (004) Bragg reflection as a function of CBr_4 fluxes



- Presence of GeSnC peak: successful GeSnC growth with atomic H
- Peak shifts to lower angle: atomic H might etch some C from growth surface compare with growth with atomic H

XRD ω-2θ scans about GaAs (004) Bragg reflection with and without atomic H

✓ Possible to grow High Crystal Quality GeSnC epitaxial layer with or without atomic H
✓ Minimum substitutional content achieved: Sn= 4% and C=3%

Conclusions/Future Work

- Rutherford backscattering spectrometry (RBS): Quantifying C-C defects
- Photoluminescence (PL) : Quantifying other kind of defects
- Secondary Ion Mass Spectrometry (SIMS): Quantifying total contents

References

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2. R. Chen et al., Increased photoluminescence of strain-reduced, high-Sn composition $Ge_{1-x}Sn_x$ alloys grown by molecular beam epitaxy, Applied Physics Letters, 99 (2011) 181125.
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4. C.A. Stephenson, M.A. Wistey et al., Band Anticrossing in Dilute Germanium Carbides Using Hybrid Density Functionals, Journal of Electronic Materials, 45 (2015) 2121-2126.
5. C.A. Stephenson, M.A. Wistey et al., Band structure of germanium carbides for direct bandgap silicon photonics, Journal of Applied Physics, 120 (2016).

Acknowledgements

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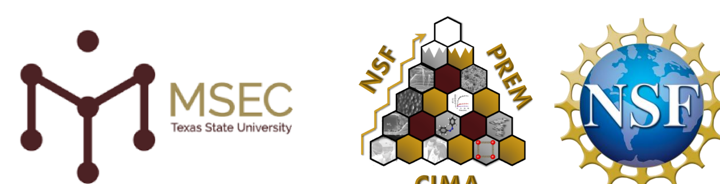

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Substitutional C: Raman Spectroscopy

- Ge-Sn peak at 263 cm^{-1} is wide and hidden by shoulder of Ge-Ge peak
- Substitutional Ge-C incorporation is verified by Raman Peak at 530 cm^{-1}

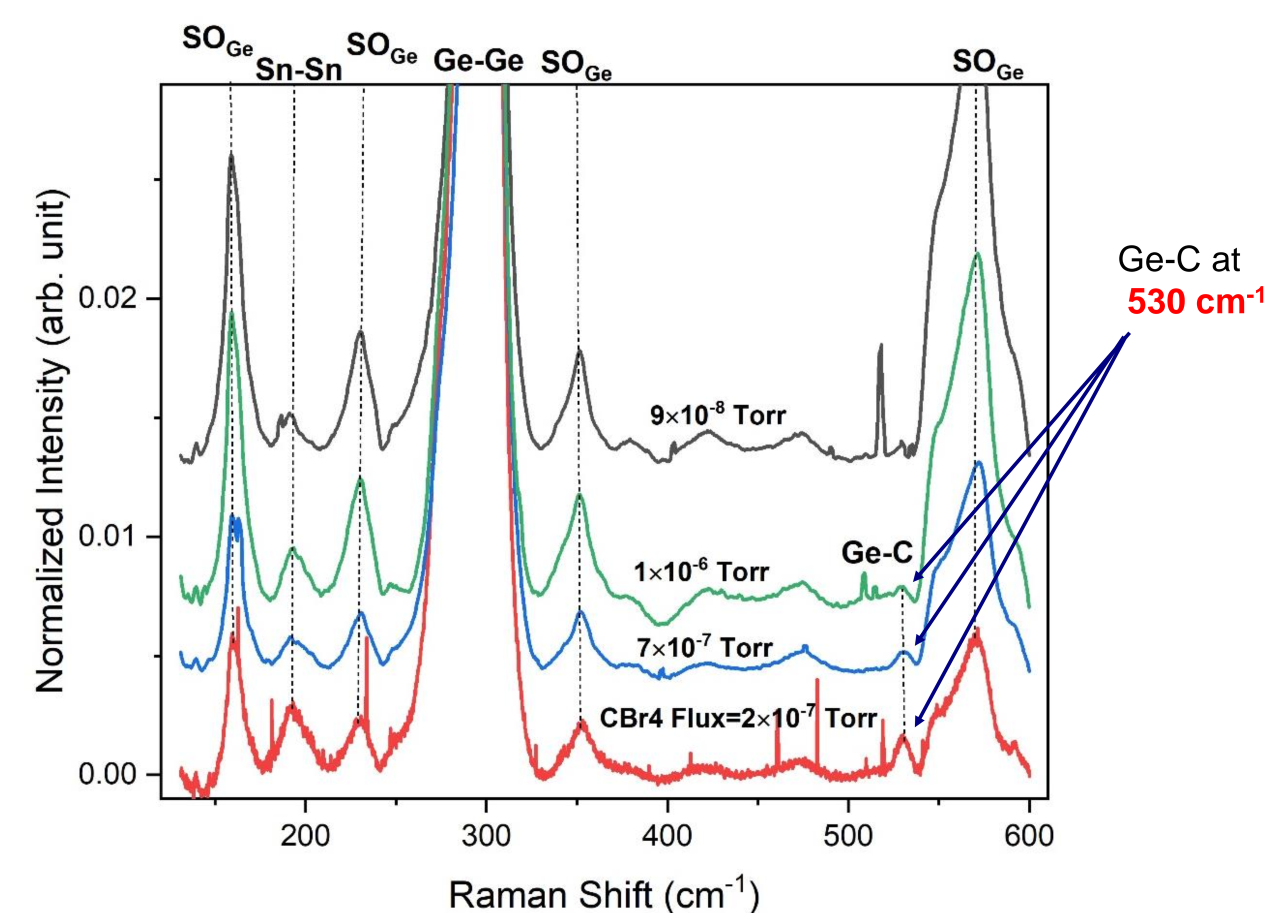
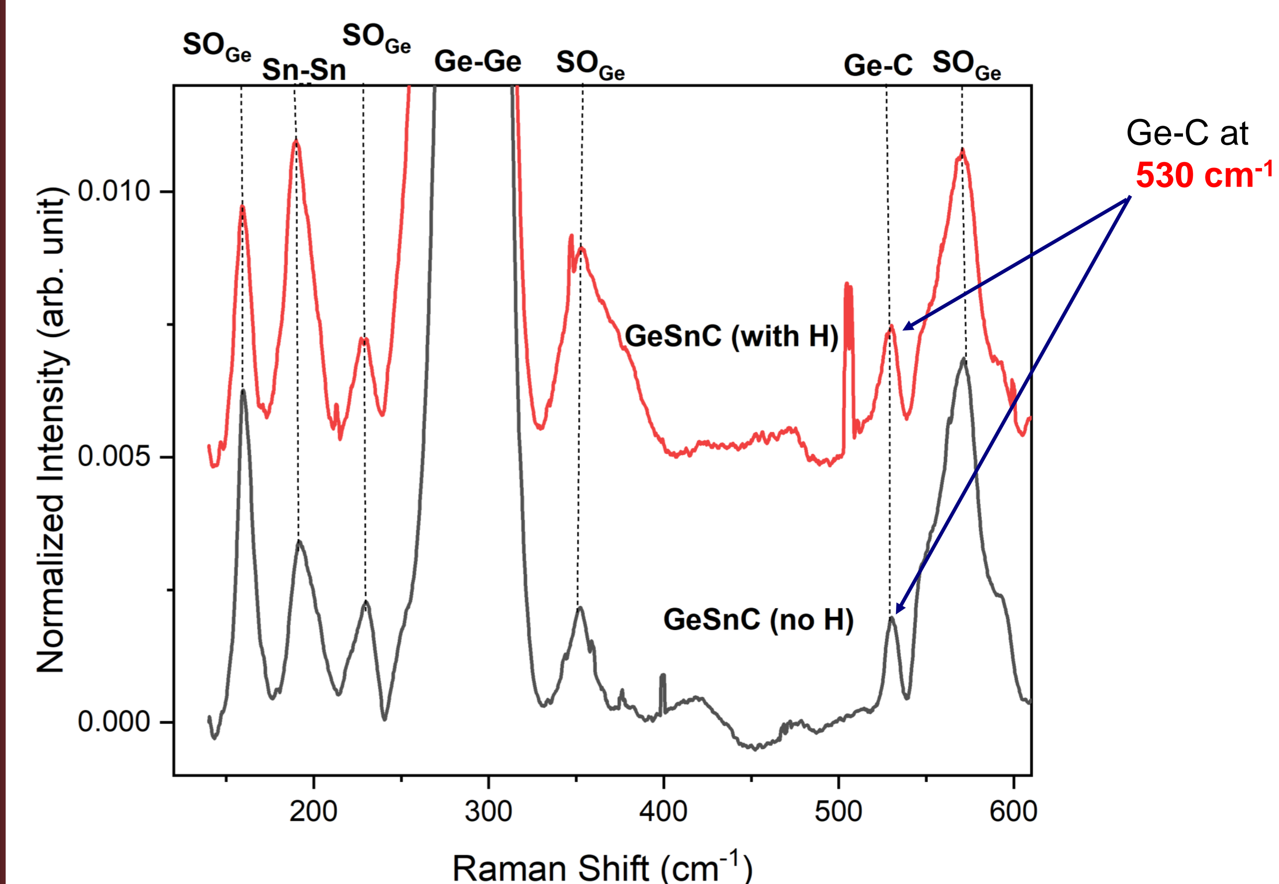


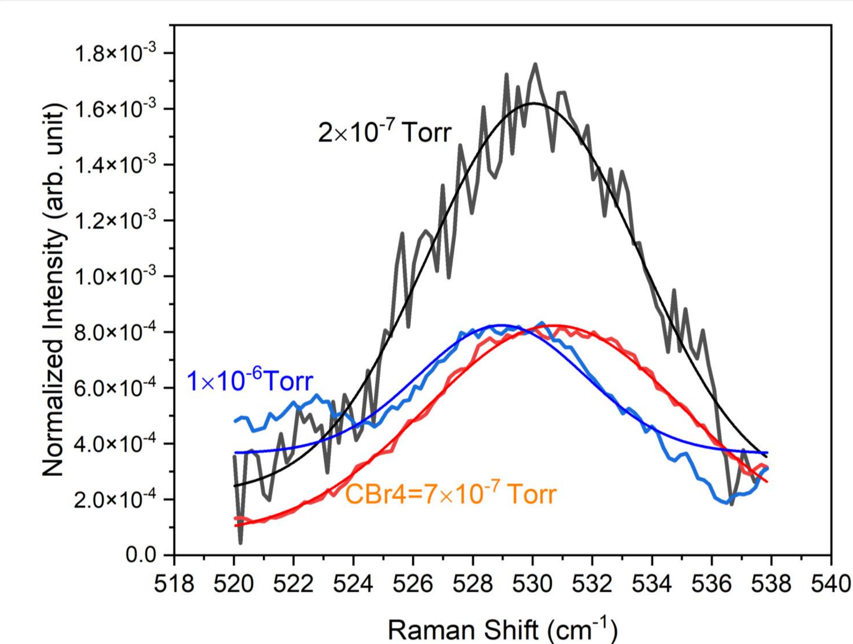
Fig. 5 Raman spectra of GeSnC as a function of CBr_4 fluxes



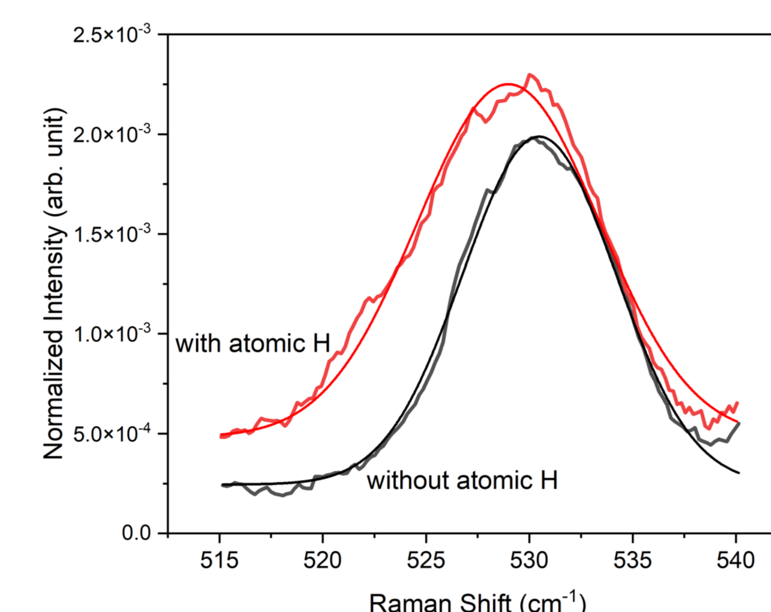
Raman spectra of GeSnC with and without atomic H

✓ C incorporation can be controlled by CBr_4 flux
✓ Both approaches (with or without atomic H) can incorporate substitutional C

Substitutional C: Raman Spectroscopy (cont.)



Ge-C at 530 cm^{-1} of variable CBr4 fluxes with Gaussian peak fitting



Ge-C at 530 cm^{-1} with Gaussian peak fitting

✓ Ge-C peak for substitutional carbon is well fitted with Gaussian fitting
✓ Both approaches (with or without atomic H) has small FWHM (~9 cm^{-1}) which indicates good crystal quality